Optimal Risk Adoption and Capacity Investment in Technological Innovations

Lars H. Sendstad, Michail Chronopoulos, and Verena Hagspiel

***Abstract*—Technological innovations often formulate new market regimes and create incentives to abandon existing, less attractive ones. However, this decision depends not only on market forces, such as economic and technological uncertainty, but also on attitudes toward risk. Although greater risk aversion typically raises the incentive to postpone investment, the impact of risk aversion becomes more complex when a firm has discretion over both the timing and the size of a project. We develop a utility-based regime-switching framework in order to analyze how a firm with discretion over investment timing and project scale may choose to abandon an existing market regime to enter a new one. Results indicate that greater risk aversion hastens investment in an existing regime by decreasing the amount of installed capacity, but delays its abandonment, thereby hindering the transition to a new one. In contrast, greater demand uncertainty in the new market regime raises the value of the investment opportunity and, in turn, the incentive to abandon the existing regime. Furthermore, we find that uncertainty over the arrival of a technological innovation may accelerate investment in the existing regime and reduce the relative loss in project value in the absence of managerial discretion over project scale.**

***Index Terms*—Investment analysis, real options, regime switching, risk aversion, technological innovation.**

I. Introduction

In the past few decades, the rapid pace of innovation and intense research and development (R&D) activities in many industries, such as information technologies, renewable energy (RE), and telecommunications, has resulted in several technological innovations. Examples include the major change that the photography industry underwent in the 1990s, when the traditional film was replaced by digital photography. Kodak, one of the major market players in the USA for traditional film, failed to keep up with many of the innovations brought by the digital era. As digital cameras became popular and reduced the need for photographic film, Kodak filed for bankruptcy in 2012 [37]. Similarly, Nokia's slow reaction to adopting prominent mobile software and positioning itself strategically next to Apple and Samsung led to a decline in profits. However, through a strategic sale of its failing handset business, Nokia acquired sufficient capital to pivot into the network equipment industry through several major acquisitions [38].

Similarly, in the energy sector, RE technologies are rapidly establishing a presence in the energy market and are becoming less reliant upon heavy subsidies or other policy interventions [40]. This green growth is transforming energy markets throughout the world and has led many companies to alter their investment strategies, drastically. For example, Scottish Power, one of the big six U.K. energy firms, has recently decided to completely abandon fossil fuels in favor of wind power [25]. Also, Ørsted, a Danish energy company that was operating in dwindling North sea fields for oil and gas with ailing connected gas and coal power plants, shed all its fossil fuel assets and used the proceeds to enter the RE industry through wind farm investments [39].

The aforementioned examples illustrate how timely technology switch is key for corporate strategy, as it may determine the success or failure of a company as a whole in any industry that is subject to a rapid pace of innovation. However, this decision becomes rather complex when it entails irreversible capacity investment in the light of evolving uncertainties and risk aversion. Indeed, although an early transition to a new market regime allows a firm to limit its exposure to downside risk from remaining in a declining old market, waiting enables the firm to observe the market and make a more informed irreversible capacity investment decision.

By analyzing this tradeoff, our contribution to the existing literature is threefold.

1) We develop a utility-based regime-switching framework for analyzing the decision to invest in and subsequently abandon the existing regime due to the arrival of a technological innovation;
2) We show how attitudes toward risk as well as economic and technological uncertainty impact the optimal regime-switching strategy in terms of both the optimal investment and capacity-sizing decision. Specifically, we find that risk aversion accelerates investment by raising the incentive to build a smaller project, while greater price sensitivity to project scale lowers the amount of installed capacity, thereby decreasing the incentive to abandon an existing market regime. Furthermore, we find that greater demand uncertainty in the existing (new) regime lowers (raises)

Manuscript received August 20, 2020; revised December 26, 2020; accepted January 27, 2021. This work was supported by the Research Council of Norway under Grants 268093 and 274569. Review of this manuscript was arranged by Department Editor D. Cetindamar. *(Corresponding author: Lars H. Sendstad.)*

Lars H. Sendstad and Verena Hagspiel are with the Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, 7491 Trondheim, Norway (e-mail: lars.h.sendstad@ntnu.no; verena.hagspiel@ntnu.no).

Michail Chronopoulos is with the Cass Business School, City University of London, London EC1Y 8TZ, U.K., and also with the Department of Business and Management Science, Norwegian School of Economics, 5045 Bergen, Norway (e-mail: michalis.chronopoulos@city.ac.uk).

Digital Object Identifier 10.1109/TEM.2021.3056142

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

the incentive to abandon the existing regime in order to invest in the new one.

3) We provide managerial insights for investment decisions based on analytical and numerical results.

The rest of this article is organized as follows. We proceed by discussing some related work in Section II and introduce assumptions and notation in Section III. The problem of investment in a new market regime is addressed in Section IV-A. In Section IV-B, we tackle the problem of abandoning an old regime in order to invest in a new one, and in Section IV-C, we analyze the problem of optimal investment and capacity sizing under regime switching. Section V provides numerical examples for each case. Finally, Section VI concludes this article.

II. Related Work

Real options theory accounts for decision making under uncertainty while reflecting the flexibility from embedded managerial discretion. Therefore, it has been widely adopted for analyzing problems such as the optimal entry to and exit from a project. However, formulations of these problems have been mainly developed under the assumption of complete financial markets or a risk-neutral decision maker [14], [30], [31]. Such formulations are not pertinent to analyzing investment in technological innovations, since these often entail idiosyncratic risk that cannot be diversified, and therefore, decision makers may exhibit risk aversion. Indeed, the underlying commodities of such projects are not likely to be freely traded, which prevents the construction of a replicating portfolio. In turn, the assumption of hedging via spanning assets breaks down and a contingent-claim approach cannot be used for project and option valuation. Hence, analytical methods for capital budgeting and risk assessment must be developed via dynamic programming, which uses a subjective discount rate to maximize the expected discounted utility of the profits of a risk-averse decision maker.

Examples of early work that attempts to reconcile risk aversion with real options theory but ignores regime switching include [21], in which Henderson and Hobson extend the work of Merton [32] by introducing market incompleteness via the inclusion of a risky asset on which no trading is allowed. In the same line of work, Henderson [20] assumes that a risky asset that is correlated with the investment payoff can be used to hedge only part of the uncertainty associated with the investment payoff, so that the remaining risk is idiosyncratic. Results indicate that higher risk aversion or lower correlation between the project value and the hedging asset, i.e., greater idiosyncratic risk, lowers both the option value and the investment threshold. This happens because the decision maker wants to reduce uncertainty by locking-in a value for the investment payoff. By contrast, Hugonnier and Morellec [22] account for a decision maker's risk aversion via a constant relative risk aversion (CRRA) utility function and show that risk aversion erodes the value of a project and raises the required investment threshold. Extensions in the same line of work that allow for operational flexibility and discretion over project scale are presented in [6] and [7].

Regime-switching frameworks for investment under economic uncertainty that allow for attitudes toward risk but ignore Markov switching and discretion over project scale include [1] and [2]. These frameworks assume that the structure of the underlying stochastic process may be affected by either a change in volatility while holding the drift fixed (see [2]) or a change in drift while holding the volatility constant (see [1]). Their results challenge those of the traditional real options literature by showing how increasing uncertainty does not necessarily decelerate investment. An extension of [1] and [2] that considers a structural change of the underlying stochastic process in terms of both the drift and the volatility is presented in [28]. More recently, Chronopoulos and Lumbreras [8] have developed a Markov regime-switching model for investment under uncertainty and find that, depending on market-regime asymmetry, greater risk aversion and price uncertainty in a new regime may accelerate regime switching. However, their model assumes an exogenous price process and ignores the flexibility to scale the size of a project.

In the area of investment and capacity sizing, examples of early work include [13] and [33]. The former considers a firm that expands its capital stock incrementally with operational flexibility, while the latter allows for discrete capacity sizing and develops a model for choosing among mutually exclusive projects under uncertainty. The decision rule of [13] involves: 1) ranking the projects by capacity; 2) finding the investment threshold for each project; and 3) selecting the largest project for which the optimal threshold exceeds the current price. In the same line of work, Dangl [11] tackles the problem of investing in a project with continuously scalable capacity and finds that demand uncertainty raises the optimal capacity and makes waiting the optimal strategy even when demand is high. Another extension of [13] is presented by Décamps *et al.* [12], who identify a second waiting region around the indifference point between the net present values (NPVs) of two projects. Within this region, a firm will select the smaller (larger) project if the price drops (increases) sufficiently. Applications of these models to RE investment are presented in [5] and [16], while policy-oriented applications are described in [3] and [35]. Nevertheless, these models are based on the assumption of risk neutrality, and therefore, attitudes toward risk are not taken into account.

Within the context of investment in technological innovations, Hagspiel *et al.* [19] consider a risk-neutral price-setting firm that faces both technological change and a declining profit stream. The firm can abandon an established technology by either exiting the corresponding market regime permanently or by investing in a new one. However, the new regime is assumed to be available, and therefore, technological uncertainty is not considered. Their results indicate that, with (without) discretion over capacity, the relationship between the optimal investment threshold and economic uncertainty is monotonic (nonmonotonic). In addition, they find that the firm abandons the current regime more easily when economic uncertainty is high and when the market for the innovative product is very attractive. Considering the case of electric vehicles, Lukas *et al.* [27] study the impact of uncertainty over the technological life cycle on the decision to

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

invest and scale the capacity of a project under risk neutrality. They find that the investment threshold follows an S-curve, segmented with respect to the optimal capacity choice, which depends on the degree of product life-cycle uncertainty. Filomena *et al.* [15] analyze the problem of technology selection and capacity investment for electricity generation in a competitive environment under uncertainty, considering: 1) the portfolio of technologies; 2) each technology's capacity; and 3) the technology's production level for every scenario. Results indicate that portfolio diversification arises even with risk-neutral firms and technologies with different cost expectations. Using plug-in electric vehicles as an example, Kauppinen *et al.* [26] analyze the impact of multiple sources of uncertainty on a sequential investment decision and show that lower growth rate might induce earlier investment when the time to build is relatively long.

Since attitudes toward risk and discretion over both investment timing and project scale may impact the optimal investment policy significantly, we explore their interaction and combined impact in this article. The scope of our model does not include the option to choose between alternative technologies (market regimes) as in [18]. Instead, we emphasize on how demand and technological uncertainty interact to affect the decision to invest in an established market regime and subsequently abandon it in order to enter a new one. Specifically, our work builds upon and complements the framework of [8] and [19]. In [19], it is shown how higher profitability of a new technology increases the incentive to adopt it earlier but invest in smaller capacity. However, in our setting, a more profitable new technology leads to earlier adoption yet with a higher capacity. In addition, we allow for risk aversion and technological uncertainty and find that both greater risk aversion and innovation rate accelerate technology adoption. Also, the latter demonstrates how greater price uncertainty and risk aversion may impact the timing of a regime switch, but ignore how capacity sizing decisions may be affected. Indeed, most of the results are reversed since a risk-averse firm can control its risk exposure via capacity sizing. Consequently, the contribution to this line of work is driven by the interaction between risk aversion and discretion over project scale under demand and technological uncertainty, features that are considered separately in the existing literature. Additionally, our framework offers a methodological contribution to the literature that addresses the impact of risk aversion on capacity investment via a utility-based framework assuming a price-taking firm, i.e., an exogenous price process, thus ignoring the feedback effect of capacity expansion on the optimal capacity investment policy.

By incorporating attitudes toward risk via a hyperbolic absolute risk aversion (HARA) utility function, we find that the interaction between demand and technological uncertainty is rather strong and that market regime asymmetry can impact the decision to abandon an existing regime in order to switch to a new one, considerably. Specifically, we find that greater (lower) economic uncertainty in the new market regime raises (reduces) the value of the associated investment opportunity and increases (decreases) the incentive to abandon the existing market regime. However, greater economic uncertainty in the existing regime raises the value of waiting, thereby increasing the incentive to postpone abandonment and delaying entry in the new regime. Furthermore, we show how greater likelihood of a technological innovation lowers the relative loss in value due to an incorrect capacity choice.

III. Model Setup

We consider a firm with a perpetual option to invest in a project of infinite lifetime facing demand and technological uncertainty. The firm has discretion over both the time of investment and the size of the project and faces a multiplicative inverse demand function [19], [23], [36]. Thus, the price process $\{P_t^{(k)}, t \geq 0\}$, where t denotes time, depends not only on the demand shock process $\{\Theta_t^{(k)}, t \geq 0\}$, but also on the output Q_t. This relationship is described as follows:

$$P_t^{(k)} \left(\Theta_t^{(k)}, Q_t\right) = \Theta_t^{(k)} \left(1 - \eta Q_t\right). \tag{1}$$

where η is a positive constant reflecting the responsiveness of price to project scale, and $k = 1, 2, 3$ are different market regimes. In terms of context, η should generally be considered regime dependent; however, if the firm is using an innovative technology in the same market, η would be constant across regimes. This would be the case, for example, with offshore wind and oil production if both production technologies supplied the same energy market.

The demand shock process follows a Markov-modulated geometric Brownian motion (GBM) that is described as

$$d\Theta_t^{(k)} = \mu_k \Theta_t^{(k)} dt + \sigma_k \Theta_t^{(k)} dZ_t, \;\; \Theta_0^{(1)} \equiv \Theta > 0 \tag{2}$$

where $\mu_k > 0$ denotes the annual growth rate, σ_k is the annual volatility, and dZ_t is the increment of the standard Brownian motion.

We assume that the arrival of a technological innovation follows a Poisson process $\{N_t, t \geq 0\}$ with intensity ν that is independent of $\{\Theta_t^{(k)}, t \geq 0\}$. This is particularly relevant for firms that do not engage in R&D but invest in technologies developed by R&D companies (as the firm under consideration in this article) and want to assess the viability of an investment decision with limited information about the decisions made by R&D companies. Once an innovation takes place, two things happen: 1) Regime 3 emerges; and 2) the market parameters for the existing technology switch from Regime 1 to Regime 2. We assume that the emergence of a new market regime reduces the attractiveness of the existing one so that $\mu_3 > \mu_1 > \mu_2$.[1] Note that the volatility can vary among the different regimes. Although technological breakthroughs tend to reduce the attractiveness of mature technologies, the volatility associated with the new market regime may initially be higher than that in the existing regime. Similarly, the gradual deterioration of Regime 1 following the arrival of the new technology may be either steady or volatile. Therefore, we do not pose any particular restriction

[1] We consider the profitability in each regime to be known, and hence, we do not consider the potential to learn as time passes by Thijssen and Bregantini [41].

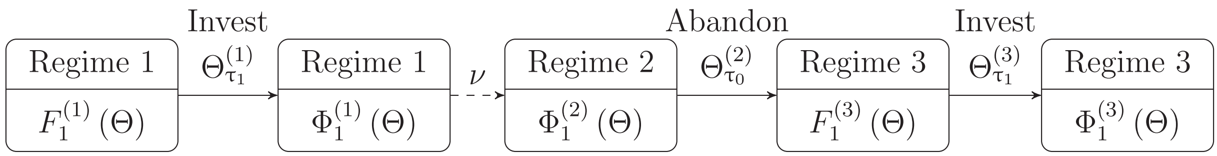

Fig. 1. State-transition diagram.

on the relationship between σ_1, σ_2, and σ_3, but, instead, we let $\sigma_3 \gtrless \sigma_1$ and $\sigma_2 \gtrless \sigma_1$.

The scenario we analyze in this article is illustrated in Fig. 1. Here, the firm initially holds the option to invest in Regime 1, and upon exercising the option at the critical threshold $\Theta^{(1)}_{\tau_1}$, it receives the expected utility of the active project in Regime 1. Once an innovation occurs, market parameter values for the existing technology switch from Regime 1 to Regime 2, while a new market regime emerges. The firm abandons the old market at the critical threshold $\Theta^{(2)}_{\tau_0}$ and receives the option to enter Regime 3.[2] Note that the irreversibility of the decision to invest in or abandon a market regime combined with demand uncertainty creates the incentive for the firm to wait for demand uncertainty to resolve by accruing relevant information before making an irreversible decision.

The firm's preferences are described by a functional $U(\cdot)$ taken from the HARA class of utility functions, namely, a power function with CRRA, indicated as

$$U(P_t) = \frac{1}{\gamma} P_t^{\gamma}. \tag{3}$$

However, note that our framework can accommodate a wide range of utility functions, such as a constant absolute risk aversion and a CRRA utility function.

The operating cost is fixed and denoted by c (\$/unit), and the cost of abandoning the existing regime is fixed and denoted by E (\$) [4]. In contrast, the investment cost $I(\cdot)$ (\$) is a linear function of the capacity, indicated as

$$I^{(k)}(Q) = b^{(k)} Q \tag{4}$$

where $b^{(k)}$ is constant. In line with [23], we assume that the firm always produces at full capacity, Q. This is often referred to as the *clearance* assumption and arises when it is costly to ramp up and down capacity or when commitments to workers and suppliers hinders temporary adjustments [19]. For ease of exposition, we set $I^{(k)}(Q) \equiv I^{(k)}$.

Also, we let $i = 0, 1$ denote the state of the project (technology) in terms of being active ($i = 1$) or abandoned ($i = 0$). We let $\tau_i^{(k)}$ denote the optimal time of investment or abandonment of a technology in Regime k, $\Theta^{(k)}_{\tau_i}$ denote the corresponding optimal investment threshold, and $Q^{(k)}$ denote the optimal capacity. Also, $F^{(k)}_{\tau_i}(\cdot)$ is the maximized expected value of the option to invest in or abandon a regime and $\Phi^{(k)}_{\tau_i}(\cdot)$ is the maximized expected utility of the active project in Regime k. For example, the time of investment in Regime 1 is denoted by $\tau_1^{(1)}$, and the corresponding optimal investment threshold and optimal capacity are denoted by $\Theta^{(1)}_{\tau_1}$ and $Q^{(1)}$, respectively.

[2] The option to make a gradual transition from the old to the new market regime instead of a direct abandonment of the old regime may also be considered within the same framework, but it is not within the scope of this article.

IV. Model

A. *Regime 3*

The value function within each market regime is determined via backward induction, and the optimal investment policy in each state is formulated by adopting a nested optimal stopping time approach. Therefore, we begin by assuming that, after having just exited the second regime, the firm is in an inactive state and considers investing in the third one. Note that the utility function in (3) is not separable in P_t, and therefore, following the same approach as [10] and [22], the key insight is to decompose the cash flows of the project into disjoint time intervals, as illustrated in Fig. 2. Therefore, we assume that the capital required for the realization of the project is initially invested in a risk-free asset, e.g., a certificate of deposit, and earns a risk-free rate, r, up to time $\tau_1^{(3)}$. At time $\tau_1^{(3)}$, the firm swaps the risk-free cash flow for the risky cash flow that the project generates and fixes the capacity of the project. We assume that the operating cost is 0 in Regime 3.[3] Also, we denote by ρ and r the subjective and risk-free discount rate, respectively, and assume that both discount rates are greater than μ_k.[4] The objective is to determine the investment policy that maximizes the time-zero expected discounted utility of all the cash flows of the project. This is indicated as follows:

$$\mathbb{E}_{\Theta}\left[\int_0^{\tau_1^{(3)}} e^{-\rho t} U\left(r I^{(3)}\right) dt + \int_{\tau_1^{(3)}}^{\infty} e^{-\rho t} U\left(\Theta_t^{(3)}\left(1 - \eta Q^{(3)}\right) Q^{(3)}\right) dt\right] \tag{5}$$

where $\mathbb{E}_{\Theta}[\cdot]$ denotes the expectation operator conditional on the initial value of the demand shock parameter, Θ.

By decomposing the first integral in (5) and rewriting it as in (6), we note that the first term in (6) is deterministic, and therefore, the optimization objective is reflected in the second

[3] This can be motivated by the operation and maintenance costs of RE such as offshore wind investments, which are only about 15% of the levelized cost of energy, i.e., total cost [24].

[4] This assumption is required in order to ensure the convergence of the firm's value functions [14, p. 138].

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

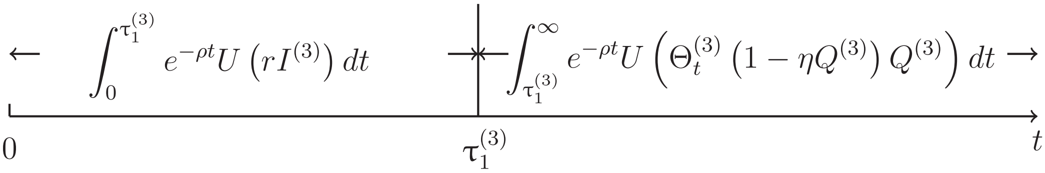

Fig. 2. Irreversible investment in Regime 3.

term

$$\int_0^\infty e^{-\rho t} U\left(rI^{(3)}\right) dt + \mathbb{E}_\Theta\left[\int_{\tau_1^{(3)}}^\infty e^{-\rho t}\left[U\left(\Theta_t^{(3)}\left(1-\eta Q^{(3)}\right)Q^{(3)}\right) - U\left(rI^{(3)}\right)\right] dt\right]. \tag{6}$$

Next, we rewrite the second term in (6) as in (7) using the law of iterated expectations and the strong Markov property of the GBM. The latter states that the values of the price process after time $\tau_1^{(3)}$ are independent of the values before $\tau_1^{(3)}$ and depend only on the value of the process at the time of investment in Regime 3, $\tau_1^{(3)}$. The objective is to determine the first passage time $\tau_1^{(3)}$ of the demand shock parameter through the threshold $\Theta_{\tau_1}^{(3)}$, i.e., $\tau_1^{(3)} = \inf\{t > 0 : \Theta_t \geq \Theta_{\tau_1}^{(3)}\}$.

$$F_1^{(3)}(\Theta) = \sup_{\tau_1^{(3)} \in \mathcal{S}} \mathbb{E}_\Theta\left[e^{-\rho\tau_1^{(3)}} \mathbb{E}_{\Theta_{\tau_1}^{(3)}} \left[\int_0^\infty e^{-\rho t}\left[U\left(\Theta_t^{(3)}\left(1-\eta Q^{(3)}\right)Q^{(3)}\right) - U\left(rI^{(3)}\right)\right] dt\right]\right]. \tag{7}$$

Note that the inner conditional expectation's independence from $\Theta_{\tau_1}^{(3)}$) means that the two expectations in (7) may be separated, as indicated in (8). Hence, the firm's maximized value of investment opportunity is expressed in (8) as the product of the stochastic discount factor (first term) and $\Phi_1^{(3)}(\Theta_{\tau_1}^{(3)})$, which denotes the expected utility of the project's cash flows maximized with respect to capacity (second term), i.e.,

$$F_1^{(3)}(\Theta) = \sup_{\tau_1^{(3)} \in \mathcal{S}} \mathbb{E}_\Theta\left[e^{-\rho\tau_1^{(3)}}\right] \Phi_1^{(3)}\left(\Theta_{\tau_1}^{(3)}\right). \tag{8}$$

As shown in Proposition 1, it is possible to derive the analytical expression for the expected utility of a perpetual stream of cash flows when the demand shock parameter follows a Markov-modulated GBM. In turn, this facilitates insights on how attitudes toward risk impact the expected utility of a project within a regime-switching environment and enables the analysis of the feedback effect of capacity choice on price under risk aversion. This is a critical contribution to the real options literature for capacity investment under risk aversion [7] that typically assumes an exogenous price process, and, therefore, ignores the feedback effect of project scale on the output price. Indeed, when considering how greater economic uncertainty raises the required investment threshold and, in turn, the amount of installed capacity [11], it is crucial to account for the impact of capacity on the output price, particularly when the former increases to considerably high levels.

Proposition 1: The expected utility of a perpetual stream of cash flows $P_t(\Theta_t^{(k)}, Q^{(k)})Q_t^{(k)}$, where $\Theta_t^{(k)}$ follows a Markov-modulated GBM, is

$$\mathbb{E}_\Theta\left[\int_0^\infty e^{-\rho t} U\left(\Theta_t^{(k)}\left(1-\eta Q^{(k)}\right)Q^{(k)}\right) dt\right] = \mathcal{A}^{(k)} U\left(\Theta^{(k)}\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)$$

where

$$\mathcal{A}^{(k)} = \frac{\beta_{1\,k}\beta_{2\,k}}{(\rho+\nu\mathbb{1}_{k=1})(\gamma-\beta_{1\,k})(\gamma-\beta_{2\,k})}$$

and $\mathbb{1}_{k=1}$ is an indicator function, while β_{jk} are the roots of the quadratic $\frac{1}{2}\sigma_k^2\beta(\beta-1)+\mu_k\beta-(\rho+\nu\mathbb{1}_{k=1})=0$, $j = 1, 2$ and $k = 1, 2, 3$.

Note that at time $\tau_1^{(3)}$, the firm exercises the investment option and must determine the optimal size of the project for the corresponding level of the demand shock parameter $\Theta_{\tau_1}^{(3)}$. Hence, the objective of the firm when exercising its investment opportunity is $\max_{Q^{(3)}} \Phi_1^{(3)}(\Theta_{\tau_1}^{(3)})$, where

$$\Phi_1^{(3)}\left(\Theta_{\tau_1}^{(3)}\right) = \mathcal{A}^{(3)} U\left(\Theta_{\tau_1}^{(3)}\left(1-\eta Q^{(3)}\right)Q^{(3)}\right) - \frac{1}{\rho} U\left(rI^{(3)}\right). \tag{9}$$

By applying the first-order necessary condition (FONC) to the unconstrained optimization problem (9), we obtain the condition for the optimal capacity. The optimal capacity for a given output price in Regime 3 is given implicitly as

$$\frac{\rho\mathcal{A}^{(3)}\Theta_{\tau_1}^{(3)\,\gamma}}{(rb)^\gamma}\left(1-2\eta Q^{(3)}\right)\left(1-\eta Q^{(3)}\right)^{\gamma-1} = 1. \tag{10}$$

By setting $\gamma = 1$, we can derive the analytical expression for the optimal capacity under risk neutrality, indicated as follows:

$$\frac{\partial}{\partial Q^{(3)}}\Phi_1^{(3)}\left(\Theta_{\tau_1}^{(3)}\right) = \frac{1}{2\eta}\left[1 - \frac{rb(r-\mu_3)}{\rho\Theta_{\tau_1}^{(3)}}\right]. \tag{11}$$

Next, we assume that the demand shock parameter is too low to justify immediate investment, and therefore, the firm needs to wait until it hits a sufficiently high threshold. Note that we can write the stochastic discount factor as $\mathbb{E}_\Theta[e^{-\rho\tau_i^{(k)}}] = (\frac{\Theta}{\Theta_{\tau_i}^{(k)}})^{\beta_{jk}}$ [14], where β_{jk} is the positive ($\beta_{1\,k}$) or negative ($\beta_{2\,k}$) root of the quadratic $\frac{1}{2}\sigma^2\beta(\beta-1)+\mu\beta-(\rho+\nu\mathbb{1}_{k=1})=0$. Therefore, $F_1^{(3)}(\Theta)$ can be expressed, for $\Theta < \Theta_{\tau_1}^{(3)}$, as follows:

$$F_1^{(3)}(\Theta) = \max_{\Theta_{\tau_1}^{(3)}>\Theta} \left(\frac{\Theta}{\Theta_{\tau_1}^{(3)}}\right)^{\beta_{13}} \Phi_1^{(3)}\left(\Theta_{\tau_1}^{(3)}\right). \tag{12}$$

By applying the FONC to the unconstrained optimization problem (12), we obtain the expression for the optimal investment threshold that is indicated in (13). Next, by inserting (13) into (10), we derive the analytical expression for optimal capacity, as indicated in (14). Note that, under risk neutrality, (13) and (14) simplify the analytical solution for the optimal investment threshold and optimal capacity described in [23]. Note that η only impacts the optimal capacity as a scaling factor in Regime 3, as we will see in the numerical results; however, the optimal investment threshold is unaffected. Hence, allowing η to be different in Regime 3 from the other regimes would only shift the value of the option to invest in the third regime. Hence, in order to limit the number of moving parts in this model, we have decided to keep η fixed across regimes.

Proposition 2: Under a HARA utility function, the optimal investment threshold and optimal capacity in Regime 3 are

$$\Theta_{\tau_1}^{(3)} = \left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}} \frac{rb}{1-\eta Q^{(3)}} \tag{13}$$

$$Q^{(3)} = \frac{1}{\eta}\frac{\gamma}{\gamma+\beta_{13}}. \tag{14}$$

Given that investment decisions are often based on the NPV criterion, it is interesting to compare the expression of the optimal capacity in (14) with that of a now-or-never investment opportunity in (11). Note that parameter b is absent in (14), which implies that the firm uses the additional degree of freedom in investment timing to account for more expensive projects. Furthermore, the impact of η is cut in half, when the firm has discretion over timing. Intuitively, the firm can mitigate the impact of greater demand sensitivity by adjusting the investment timing. Also, the second-order sufficiency condition (SOSC) requires the objective function to be concave at $\Theta_{\tau_1}^{(3)}$, which is shown in Proposition 3.

Proposition 3: The objective function $F_1^{(3)}(\cdot)$ is strictly concave at $\Theta_{\tau_1}^{(3)}$ iff $\gamma < \beta_{13}$.

In Proposition 4, we show that higher risk aversion decreases the propensity to invest in greater capacity. Intuitively, risk aversion decreases the expected utility of the project, which makes a smaller capacity optimal. Hence, measures to reduce the overall risk are crucial to induce investments in RE capacity. For example, adequate financial markets to hedge price risk can limit the effect of risk aversion [29].

Proposition 4: Greater risk aversion lowers the optimal capacity and decreases the required investment threshold.

In Proposition 5, we show that greater demand uncertainty increases both the optimal capacity and the required investment threshold. Intuitively, the firm mitigates demand uncertainty by deferring the irreversible investment decision in order to learn more about future market conditions.

Proposition 5: Greater demand uncertainty raises the optimal capacity and increases the required investment threshold.

B. Regime 2

Here, we assume that the firm is active in Regime 2 and that it holds an embedded option to abandon it in order to invest in Regime 3. Note that when the firm decides to abandon the second regime, it salvages the operating cost, incurs the abandonment cost, and foregoes the revenues of the active project. Also, since the project is already active in Regime 2, the capacity may have already been set optimally either in Regime 1 or Regime 2, depending on whether an innovation occurred before the firm could invest or after. Assuming that the capacity was fixed upon investment in Regime 1 and cannot be adjusted ex-post, the expected utility of an abandoned project is described in (15) and consists of the expected utility of abandoning the second regime (first two terms) and the embedded option to invest in the third one

$$\Phi_0^{(2)}\left(\Theta_{\tau_0}^{(2)}, Q^{(1)}\right) = \frac{1}{\rho}U\left(cQ^{(1)}-rE\right) - \mathcal{A}^{(2)}U\left(\Theta_{\tau_0}^{(2)}\left(1-\eta Q^{(1)}\right)Q^{(1)}\right) + F_1^{(3)}\left(\Theta_{\tau_0}^{(2)}\right). \tag{15}$$

Following the same steps as in Section IV-A, the maximized value of the option to abandon the second regime is described in (16) for $\Theta > \Theta_{\tau_0}^{(2)}$, as a product of the stochastic discount factor and the expected NPV at abandonment. Note that, in the presence of the embedded option to invest in Regime 3, the optimal abandonment threshold must be obtained numerically

$$F_0^{(2)}\left(\Theta, Q^{(1)}\right) = \max_{\Theta_{\tau_0}^{(2)}<\Theta_{\tau_1}^{(2)}} \left(\frac{\Theta}{\Theta_{\tau_0}^{(2)}}\right)^{\beta_{22}} \Phi_0^{(2)}\left(\Theta_{\tau_0}^{(2)}, Q^{(1)}\right). \tag{16}$$

Next, we step back and assume that the firm is active in the second regime and holds the option to abandon it following a sufficient decrease in demand. The expected utility of the active project in Regime 2 is described as

$$\Phi_1^{(2)}\left(\Theta_{\tau_1}^{(2)}, Q^{(1)}\right) = \mathcal{A}^{(2)}U\left(\Theta_{\tau_1}^{(2)}\left(1-\eta Q^{(1)}\right)Q^{(1)}\right) - \frac{1}{\rho}U\left(cQ^{(1)}+rI^{(1)}\right) + F_0^{(2)}\left(\Theta_{\tau_1}^{(2)}, Q^{(1)}\right). \tag{17}$$

To emphasize the value of the option to invest in the third regime, we also determine the value of the option to abandon the second one permanently, which is indicated in (18) and we use overbar to differentiate this case. This implies that we are calculating the scenario without Regime 3, meaning that the impact of $F_1^{(3)}(\overline{\Theta}_{\tau_0}^{(2)})$ cancels in the following equation:

$$\overline{F}_0^{(2)}\left(\Theta, \overline{Q}^{(1)}\right) = \max_{\overline{\Theta}_{\tau_0}^{(2)}<\Theta_{\tau_1}^{(2)}} \left(\frac{\Theta}{\overline{\Theta}_{\tau_0}^{(2)}}\right)^{\beta_{22}} \left[\Phi_0^{(2)}\left(\overline{\Theta}_{\tau_0}^{(2)}, \overline{Q}^{(1)}\right) - F_1^{(3)}\left(\overline{\Theta}_{\tau_0}^{(2)}\right)\right]. \tag{18}$$

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

In the absence of the option to invest in Regime 3, we can obtain an analytical expression for the optimal abandonment threshold. An increase in the demand parameters η raises the optimal abandonment threshold. Intuitively, this occurs because an increase in η makes the inverse demand function more responsive to changes in capacity. Thus, greater η lowers the output price for a given capacity and, in turn, reduces the attractiveness of the second regime, thereby inducing earlier abandonment. This reveals an important testable hypotheses, since a greater η implies a smaller overall market, in which firms might be expected to abandon and transit to RE earlier if the market for fossil fuels continuous to diminish

$$\overline{\Theta}_{\tau_0}^{(2)} = \left(\frac{\beta_{12}-\gamma}{\beta_{12}}\right)^{\frac{1}{\gamma}} \frac{c\overline{Q}^{(1)} - rE}{\left(1-\eta\overline{Q}^{(1)}\right)\overline{Q}^{(1)}}. \tag{19}$$

For completeness, we also consider the case where a technological innovation occurs before the firm enters the market; however, due to lower costs associated with the old market, the firm considers to invest in Regime 2. The first-order condition for optimal capacity choice in Regime 2 is

$$\begin{aligned}
&\frac{\partial}{\partial Q^{(2)}}\Phi_1^{(2)}\left(\Theta, Q^{(2)}\right) \\
&= 0 \Rightarrow \gamma\mathcal{A}^{(2)}U(\Theta)\left[\left(1-\eta Q^{(2)}\right)Q^{(2)}\right]^{\gamma-1}\left[1-2\eta Q^{(2)}\right] \\
&- \frac{\gamma}{\rho}U\left(c+rb^{(2)}\right)Q^{(2)^{\gamma-1}} + \frac{\partial}{\partial Q^{(2)}}F_0^{(2)}(\Theta, Q^{(2)}) = 0.
\end{aligned} \tag{20}$$

With the option to delay investment, the maximized value of the option to invest in Regime 2 is described in (21) for $\Theta < \Theta_{\tau_1}^{(2)}$. Unlike Regime 3, the optimal investment threshold is now obtained numerically by applying the FONC to the unconstrained optimization problem (21) together with the optimal capacity condition from (20)

$$\begin{aligned}
F_1^{(2)}(\Theta) &= \max_{\Theta_{\tau_1}^{(2)}>\Theta}\left(\frac{\Theta}{\Theta_{\tau_1}^{(2)}}\right)^{\beta_{21}}\Phi_1^{(2)}\left(\Theta_{\tau_1}^{(2)}, Q^{(2)}\right) \\
&= A_1^{(2)}\Theta^{\beta_{21}}, \text{ where } A_1^{(2)} = \left(\frac{1}{\Theta_{\tau_1}^{(2)}}\right)^{\beta_{21}}\Phi_1^{(2)}\left(\Theta_{\tau_1}^{(2)}, Q^{(2)}\right).
\end{aligned} \tag{21}$$

The required investment threshold balances two opposing forces. On the one hand, greater demand uncertainty increases the incentive to wait and to invest later, whereas, on the other hand, the value of the option to abandon also increases, which, in turn, increases the project value and incentivizes early investment.

C. *Regime 1*

To facilitate the analysis of technological uncertainty, we derive the value functions and optimal investment thresholds in Regime 1 as the solution to a free-boundary problem. The expected utility of the active project in the first regime is indicated in (22) for $\Theta > \Theta_{\tau_0}^{(2)}$. The first and second terms on the right-hand side are the utility of the immediate profits and the second term is the expected utility in the continuation region. As the second term indicates, within an infinitesimal time interval dt, a regime switch may take place with probability νdt and the firm will receive the value function $\Phi_1^{(2)}(\Theta, Q^{(1)})$, which is already defined in (17) and consists of the value of the active project in Regime 2 and a single embedded option to abandon it. In contrast, no innovation will occur with probability $1 - \nu dt$, and the firm will continue to hold the value function $\max_{Q^{(1)}} \Phi_1^{(1)}(\Theta)$

$$\begin{aligned}
\Phi_1^{(1)}(\Theta) &= U\left(\Theta\left(1-\eta Q^{(1)}\right)Q^{(1)}\right)dt - U\left(cQ^{(1)} + rI^{(1)}\right) \\
&+ e^{-\rho dt}\left\{\nu dt \mathbb{E}_\Theta\left[\Phi_1^{(2)}\left(\Theta + d\Theta, Q^{(1)}\right)\right]\right. \\
&\left.+ (1-\nu dt)\mathbb{E}_\Theta\left[\Phi_1^{(1)}(\Theta + d\Theta)\right]\right\}, \Theta > \Theta_{\tau_0}^{(2)}.
\end{aligned} \tag{22}$$

If $\Theta < \Theta_{\tau_0}^{(2)}$, then, upon switching to the second regime, the firm will terminate operations, thus receiving the cash flows following the termination of operations in Regime 2 as well as the option to invest in the third regime, as indicated in (15)

$$\begin{aligned}
\Phi_1^{(1)}(\Theta) &= U\left(\Theta\left(1-\eta Q^{(1)}\right)Q^{(1)}\right)dt - U(cQ^{(1)} + rI^{(1)}) \\
&+ e^{-\rho dt}\left\{\nu dt \mathbb{E}_\Theta\left[\Phi_0^{(2)}\left(\Theta + d\Theta, Q^{(1)}\right)\right]\right. \\
&\left.+ (1-\nu dt)\mathbb{E}_\Theta\left[\Phi_1^{(1)}(\Theta + d\Theta)\right]\right\}, \quad \Theta \le \Theta_{\tau_0}^{(2)}.
\end{aligned} \tag{23}$$

Expanding the right-hand side of (22) and (23) using Ito's lemma, we obtain the following ordinary differential equation: where $\mathcal{L} = \frac{1}{2}\sigma^2\Theta^2\frac{\partial^2}{\partial\Theta^2} + \mu\Theta\frac{\partial}{\partial\Theta}$ is the differential operator.

The solution for (24) shown at the bottom of this page, is indicated in (25), as shown at bottom of the next page, where β_{11} and β_{21} are the roots of $\frac{1}{2}\sigma_1^2\beta(\beta-1) + \mu_1\beta - (\rho+\nu) = 0$ and $\mathcal{C}_{ik} = -\nu/[\frac{1}{2}\sigma_1^2\beta_{ik}(\beta_{ik}-1) + \mu_1\beta_{ik} - (\rho+\nu)]$. The first two terms in the top part of (25) represent the expected profit from operating in the first regime that might suddenly switch to the second. The third term reflects abandonment option from Regime 2, which is adjusted by the final term in order to account for the likelihood of falling below the investment threshold under technological uncertainty. The first three terms on the bottom part represents the expected utility of the profits from operating in the first regime, while the fourth term is the

$$\begin{cases}
[\mathcal{L} - (\rho+\nu)]\Phi_1^{(1)}(\Theta) + \nu\Phi_1^{(2)}\left(\Theta, Q^{(1)}\right) + U\left(\Theta\left(1-\eta Q^{(1)}\right)Q^{(1)}\right) - U\left(cQ^{(1)} + rI^{(1)}\right) = 0 \\
[\mathcal{L} - (\rho+\nu)]\Phi_1^{(1)}(\Theta) + \nu\Phi_0^{(2)}\left(\Theta, Q^{(1)}\right) + U\left(\Theta\left(1-\eta Q^{(1)}\right)Q^{(1)}\right) - U\left(cQ^{(1)} + rI^{(1)}\right) = 0
\end{cases} \tag{24}$$

expected utility of the cash flows from abandoning Regime 2, adjusted for technological uncertainty. The fourth term is the option to invest in Regime 3, adjusted via the fifth term because the second regime has yet to become available. If $\nu = 0$, then the third, fourth, and fifth terms in the upper branch are zero. Intuitively, $\nu = 0$ implies that no regime switching will take place, and as a result, the first technology will continue to operate in the first regime. In contrast, $\lim_{\nu\to\infty} \Phi_1^{(1)}(\Theta, Q^{(1)}) = \Phi_1^{(2)}(\Theta, Q^{(2)})$ since $\lim_{\nu\to\infty} \nu\mathcal{A}^{(1)} = 1$ and $\lim_{\nu\to\infty} \mathcal{A}^{(1)} = 0$ The condition for optimal capacity choice at investment in Regime 1 is described as follows:

$$\gamma\left[1+\nu\mathcal{A}^{(2)}\right]\mathcal{A}^{(1)}U(\Theta)\left[\left(1-\eta Q^{(1)}\right)Q^{(1)}\right]^{\gamma-1} \times\left[1-2\eta Q^{(1)}\right]-\frac{\gamma}{\rho}U\left(c+rb^{(1)}\right)Q^{(1)\gamma-1} + \frac{\partial}{\partial Q^{(1)}}\left(\mathcal{C}_{22}F_0^{(2)}(\Theta,Q^{(1)})+A_1^{(1)}\Theta^{\beta_{21}}\right)=0 \quad (26)$$

Note that if the firm invests in the first regime, then it needs to consider not only how to maximize the profit in the first regime, but also take into consideration the implications of the installed capacity in a potentially declining market (Regime 2). Intuitively, we expect to see that the firm installs a smaller project to limit its risk exposure when a technological innovation in likely to arrive.

Next, the dynamics of the option to invest in the first regime are described as follows:

$$F_1^{(1)}(\Theta)=e^{-\rho dt}\left\{\nu dt\mathbb{E}_\Theta\left[F_1^{(2)}(\Theta+d\Theta)\right] + (1-\nu dt)\,\mathbb{E}\left[F_1^{(1)}(\Theta+d\Theta)\right]\right\}. \quad (27)$$

The first term on the right-hand side of (27) indicates that, while waiting to invest in the first regime, an innovation may take place with probability νdt and the firm will receive the value function $F_1^{(2)}(\Theta)$. In contrast, with probability $1-\nu dt$ no innovation will take place, and the firm will continue to hold the value function $F_1^{(1)}(\Theta)$.

By expanding the right-hand side of (27) using Itô's lemma we obtain (28), which must be solved together with (29), i.e., the differential equation for the value of the option to abandon in the second regime

$$[\mathcal{L}-(\rho+\nu)]\,F_1^{(1)}(\Theta)+\nu F_1^{(2)}(\Theta)=0 \quad (28)$$

$$[\mathcal{L}-\rho]\,F_1^{(2)}(\Theta)=0. \quad (29)$$

Hence, the value of the option to invest in Regime 1 is obtained by solving (28) and (29) and is described as follows:

$$F_1^{(1)}(\Theta)=\begin{cases} D_1^{(1)}\Theta^{\beta_{11}}+\mathcal{C}_{12}A_1^{(2)}\Theta^{\beta_{12}}, & \Theta<\Theta_{\tau_1}^{(1)} \\ \Phi_1^{(1)}(\Theta), & \Theta\geq\Theta_{\tau_1}^{(1)} \end{cases}. \quad (30)$$

Next, $A_1^{(1)}$, $B_1^{(1)}$, $D_1^{(1)}$, $Q^{(1)}$, $\Theta_{\tau_1}^{(1)}$, and $\Theta_{\tau_0}^{(2)}$ are obtained numerically via value-matching and smooth-pasting conditions between the two branches of (25), (26), and (30).

V. Numerical Examples

A. Regime 3

For the numerical examples, we assume that $\eta = 0.05$, $b_1 = b_2 = 75$, $b_3 = 100$, $r = \rho = 10\%$, $\sigma_k = 0.25$, $\gamma \in [0.9, 1.1]$, $\mu_1 = 0\%$, $\mu_2 = -2\%$, $\mu_3 = 2\%$, $\nu = 0.1$, $\Theta = 30$, $E = 10$, and $c = 1$. Also, we assume that a new regime (technology) is more attractive in that it exhibits a higher growth rate compared to the incumbent one, yet entry entails a greater capital expenditure. In terms of context, a firm may have an oil platform that can be retrofitted to an offshore wind farm. This example fits within the general setting, where a firm develops a facility using an existing technology holding an embedded option to switch to a new one following a market regime switch that renders the latter more profitable. The irreversibility of the initial investment decision is reflected on both the associated sunk investment cost and the decommissioning cost that the firm must incur.

The left panel in Fig. 3 illustrates the option and project value as well as the maximized NPV for $\mu_3 = 1\%, 2\%$, while the right panel illustrates the impact of γ on $\Theta_{\tau_1}^{(3)}$ for $\gamma < 1$ (risk aversion), $\gamma = 1$ (risk-neutrality) and $\gamma > 1$ (risk-seeking). Note that an increase in μ_3 raises the attractiveness of Regime 3 and, in turn, the incentive to install a bigger project, also decreasing the required investment threshold. As the right panel illustrates, greater risk-aversion accelerates investment by increasing the firm's incentive to build a smaller project, and, thus, reduce exposure to downside risk, as shown in Proposition 4. This is in direct contrast to [8] and happens because a more risk-averse firm chooses a lower capacity instead of postponing the investment decision to reduce the overall risk exposure. Also, higher demand uncertainty postpones investment by raising the associated opportunity cost and, in turn, the value of waiting. Note that the association between the time of investment and the optimal price threshold is based on the property of the GBM with positive drift that indicates that the output price is expected to increase on average with time. Thus, when an investment is delayed or accelerated, the associated output price is on average higher or lower, respectively.

$$\Phi_1^{(1)}(\Theta)=\begin{cases} \left[1+\nu\mathcal{A}^{(2)}\right]\mathcal{A}^{(1)}U\left(\Theta\left(1-\eta Q^{(1)}\right)Q^{(1)}\right)-\frac{1}{\rho}U\left(cQ^{(1)}+rI^{(1)}\right) \\ +\mathcal{C}_{22}F_0^{(2)}(\Theta,Q^{(1)})+A_1^{(1)}\Theta^{\beta_{21}}, & \Theta>\Theta_{\tau_0}^{(2)} \\ \left[1-\nu\mathcal{A}^{(2)}\right]\mathcal{A}^{(1)}U\left(\Theta\left(1-\eta Q^{(1)}\right)Q^{(1)}\right)-\frac{1}{\rho+\nu}U\left(cQ^{(1)}+rI^{(1)}\right) \\ +\frac{\nu U\left(cQ^{(1)}-rE\right)}{\rho(\nu+\rho)}+\mathcal{C}_{13}F_1^{(3)}(\Theta)+B_1^{(1)}\Theta^{\beta_{11}}, & \Theta\leq\Theta_{\tau_0}^{(2)} \end{cases}. \quad (25)$$

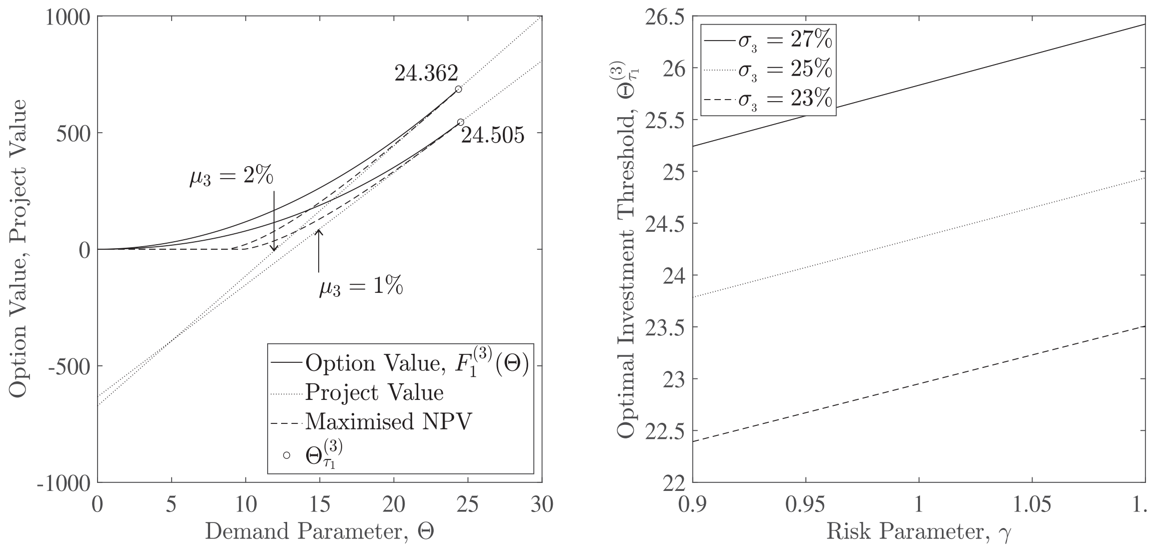

Fig. 3. Impact of μ_3 on option and project value where $\gamma = 1$ (left panel) and optimal investment threshold versus γ (right panel).

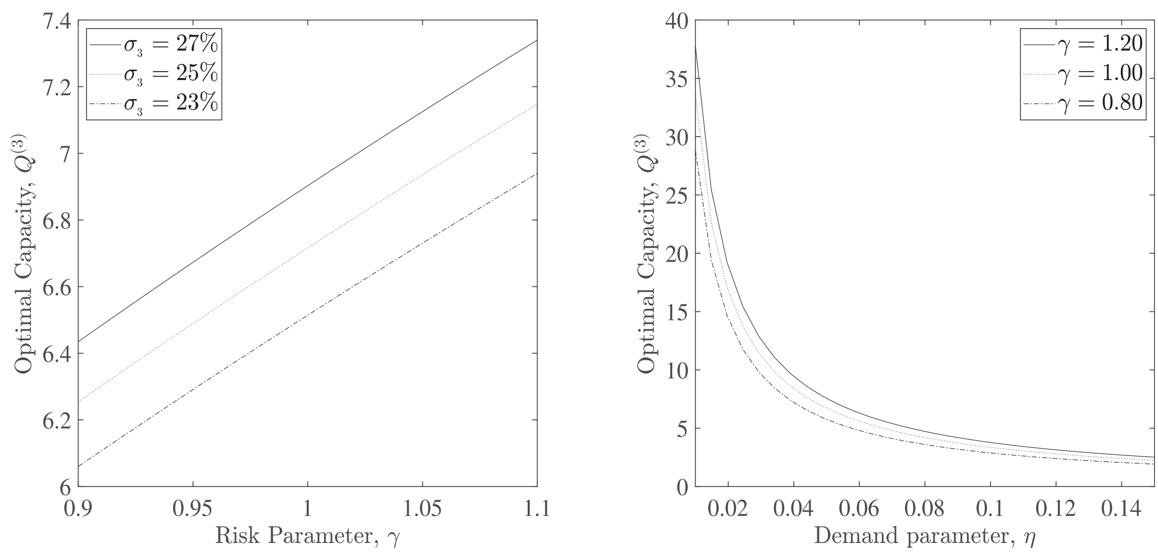

Fig. 4. Optimal capacity versus γ for $\eta = 0.05$ (left panel) and versus η (right panel).

In line with Fig. 3, the left panel of Fig. 4 indicates that it is optimal to invest in a smaller capacity when risk aversion increases, while greater demand uncertainty raises the incentive to wait and invest later in a bigger project. However, as the right panel illustrates, greater η increases the price sensitivity to project scale and leads to the installation of a smaller project, thereby making the impact of greater risk aversion more pronounced. This implies that both risk aversion and price sensitivity to project scale present significant forces that can deter a bold entry to a new market and emphasizes how managerial decisions are subject to both internal, e.g., attitudes toward risk, and external pressures reflected in the wider economic environment.

B. Regime 2

In Regime 2, a technological innovation has already altered the market, which means that the market outlook for the first technology is deteriorating. The left panel in Fig. 5 illustrates the impact of η and σ_2 on the optimal abandonment threshold. Note that a lower η implies that prices are less affected by additional capacity, which, in turn, leads to the installation of a bigger project. However, an increase in the amount of installed capacity raises the exposure to downside risk and, in turn, the incentive to abandon the project at a higher threshold. Furthermore, greater demand uncertainty in Regime 2 increases the incentive to postpone the abandonment decision. Intuitively, this happens because the firm would be reluctant to abandon Regime 2 permanently due to a temporary downturn, which is more likely when uncertainty is high. However, as the right panel indicates, an increase in demand uncertainty in Regime 3 presents and opposing force, as it raises the value of the associated investment option and, in turn, the option to abandon Regime 2. However, this is irrelevant if the option to invest in Regime 3 is not present, as illustrated by the permanent abandonment threshold.

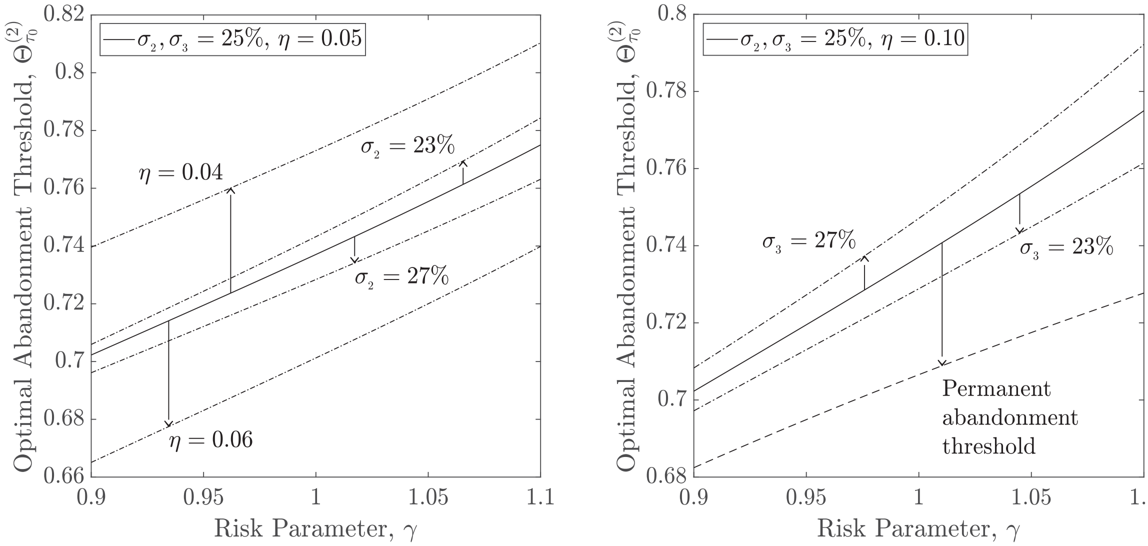

Fig. 5. Optimal abandonment threshold versus γ (left panel) and σ_3 (right panel).

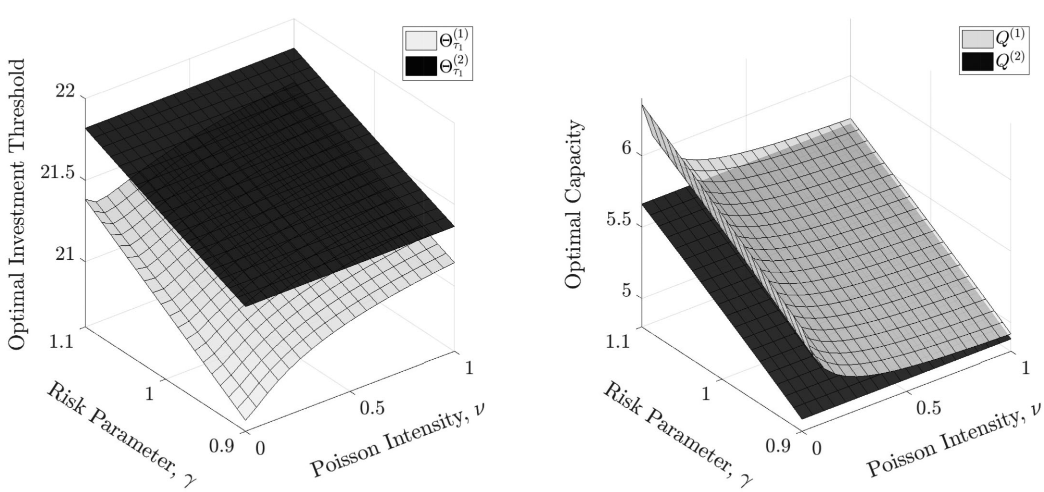

Fig. 6. Impact of ν and γ on optimal investment threshold (left panel) and optimal capacity (right panel) in Regime 1.

C. Regime 1

Fig. 6 illustrates the impact of ν and γ on the optimal investment threshold (left panel) and the optimal capacity (right panel) in Regimes 1 and 2. As the left panel indicates, greater likelihood of regime switching raises a firm's incentive to postpone investment in the first regime. Interestingly, although a nonmonotonic impact is reported in earlier literature [9], this is not particularly evident here, especially for high levels of risk aversion. Interestingly, greater likelihood of regime switching does not raise the amount of installed capacity, even though it raises the optimal investment threshold, but, instead, results in the installation of a smaller project. This seemingly counterintuitive result happens because the emergence of a new market regime reduces the attractiveness of the existing one, thereby raising the incentive to invest later in a smaller project in Regime 1. Intuitively, the firm would not want to commit to a project of large capacity that is based on a technology that will soon become obsolete. In order to establish further the intuition underlying this result, notice also how both the optimal investment threshold and the optimal capacity in Regime 1 converge under greater ν to their values in Regime 2, where a regime switch has already taken place.

Fig. 7 illustrates the impact of ν and σ_1 on the relative loss in option value due to fixed capacity, which is indicated as

$$\frac{F_1^{(1)}\left(\Theta_{\tau_1}^{(1)}, Q^{(1)}\right) - F_1^{(1)}\left(\Theta_{\tau_1}^{(1)}, Q\right)}{F_1^{(1)}\left(\Theta_{\tau_1}^{(1)}, Q^{(1)}\right)}. \tag{31}$$

The left panel in Fig. 7 indicates that, as capacity increases, the relative loss in option value diminishes when $Q < Q^{(1)}$, becomes zero for $Q = Q^{(1)}$, and increases if $Q > Q^{(1)}$. This implies that increasing demand uncertainty raises (lowers) the relative loss in option value when the amount of installed capacity is lower (greater) than the optimal one. By contrast, the right panel indicates that greater likelihood of innovation lowers the amount of installed capacity and reduces (increases) the

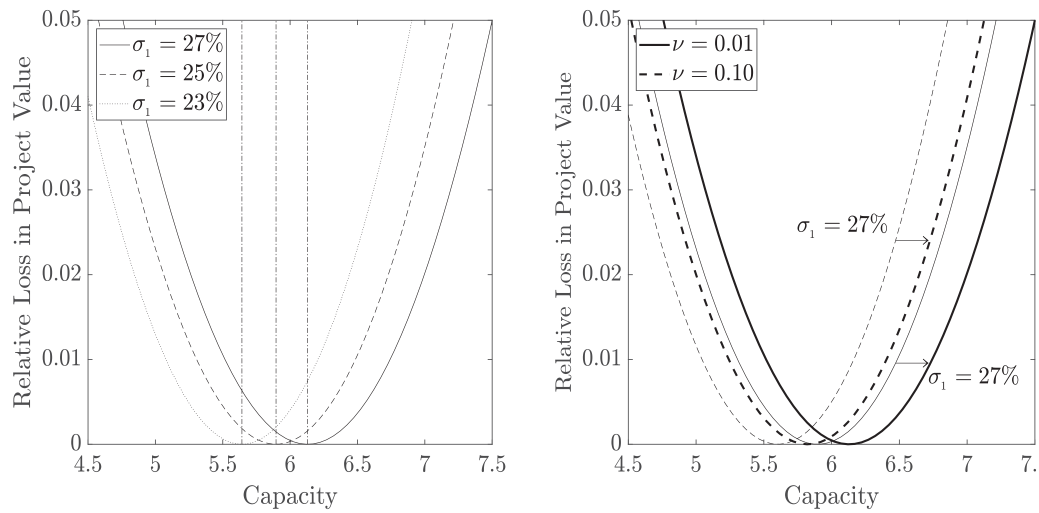

Fig. 7. Relative loss in option value due to fixed capacity in Regime 1 for $\nu = 0.1$ (left panel) and $\sigma = 25\%$ (right panel) and $\gamma = 1$ for both panels.

TABLE I
EFFECT OF INCREASING GROWTH RATE OF REGIME 3 ON THE OPTIMAL INVESTMENTS/EXIT THRESHOLDS AND ASSOCIATED CAPACITIES

μ_3	0%	1%	2%	3%
$\Theta_{\tau_1}^{(3)}$	24.734	24.505	24.362	24.306
$Q^{(3)}$	5.957	6.327	6.716	7.120
$\Theta_{\tau_0}^{(2)}$	0.737	0.745	0.763	0.808
$\Theta_{\tau_1}^{(1)}$	21.061	21.061	21.060	21.059
$Q^{(1)}$	5.604	5.604	5.604	5.604

relative loss in option value when the size of the project is lower (greater) than the optimal level. This result reveals an important implication of managerial discretion over project scale, since it implies that investment within industries, which are likely to be disrupted may benefit from a more conservative strategy.

By investigating the effect of μ_3 on the optimal investment thresholds and corresponding quantities in Table I, we can gain insight on how firms should adjust their optimal strategy. Although we find that greater growth rate in the innovative market induces earlier investment, we do not observe a smaller capacity as in [19]. This is because the firm hastens the transition by abandoning earlier instead of investing earlier. Finally, the impact of increasing market growth in Regime 3 seems negligible on the initial capacity and investment threshold. This is a common result for sequential investments [14] and stems from the ability to consider sequential investments myopically.

VI. CONCLUSION

The increasing frequency of technological innovations indicates that the developing world reflects a rapid-growing market rather than just a low-cost manufacturing base. Within this context, the viability of private firms relies crucially on investment strategies that are responsive to market conditions. Therefore, we develop a utility-based regime-switching framework in order to analyze how technological and demand uncertainties interact with attitudes toward risk to impact the decision to abandon an existing market regime in order to enter a new one. Thus, the contribution of this article was to provide an insights on the effect of managerial discretion in the light of interacting uncertainties. Specifically, by characterizing firms' expectations under risk aversion and incorporating them into a decision-support tool for sequential investment and abandonment, we provide insights on how discretion over investment timing and project scale can be used to manage risk exposure associated with the transition out of a disrupted industry. Such insights tend to be absent from the long-term economic models that support policy initiatives, yet failure to understand these properly raises the likelihood of cycles of under- or overinvestment and the cost of the associated corrective actions.

Results indicate that managerial discretion, risk aversion, and market regime asymmetry, in terms of growth assumptions and economic uncertainty, can have a crucial impact on the decision to give up an existing mature regime in order to enter a new, possibly riskier, yet more profitable one. We find that both risk aversion and price sensitivity to project scale deter a bold entry to a new market, significantly. Indeed, we show that risk aversion accelerates investment by raising the incentive build a smaller project in order to reduce exposure to downside risk. Also, greater price sensitivity to project scale lowers the amount of installed capacity and, thus, decreases both the exposure to downside risk and the incentive to abandon an existing market regime more easily. Furthermore, we find that greater demand uncertainty in the existing (new) regime lowers (raises) the incentive to abandon the existing regime in order to invest in the new one. Finally, we show how the relative loss in project value in the absence of discretion over project scale is affected by demand and technological uncertainty and how it may decrease as an innovation becomes more likely.

In terms of future research, our framework can be extended to account not only for the rapid pace of innovation and technological obsolescence, but also for the increasingly competitive environment in which technological innovations emerge. Consequently, future work should consider the impact of competition on not only the optimal investment and capacity sizing decisions [23], but also the optimal technology-adoption strategy [9], [17], [18], [34]. This will enable the further investigation of important interactions among opposing forces reflected in pre-emption, risk aversion, and economic uncertainty. Moreover, the impact of regime dependent η could be discussed in such a setting. In addition, the option to make a gradual transition from the old to the new market regime instead of a direct abandonment of the old regime may also be considered within the same framework. Finally, the real options framework presented in this article may also be reformulated in terms of Bayesian analysis in order to allow for sequential experimentation that provides information about the true profitability of a new technology, thereby informing irreversible investment in technological innovations with a regime-switching framework.

APPENDIX

Proposition 1: The expected utility of a perpetual stream of cash flows $P_t(\Theta_t^{(k)}, Q^{(k)})Q_t^{(k)}$, where $\Theta_t^{(k)}$ follows a Markov-modulated GBM, is

$$\mathbb{E}_\Theta\left[\int_0^\infty e^{-\rho t} U\left(\Theta_t^{(k)}\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)dt\right] = \mathcal{A}^{(k)} U\left(\Theta^{(k)}\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)$$

where

$$\mathcal{A}^{(k)} = \frac{\beta_{1\,k}\beta_{2\,k}}{\left(\rho+\nu\mathbb{1}_{k=1}\right)\left(\gamma-\beta_{1\,k}\right)\left(\gamma-\beta_{2\,k}\right)}$$

and $\mathbb{1}_{k=1}$ is an indicator function, while β_{jk} are the roots of the quadratic $\frac{1}{2}\sigma_k^2\beta(\beta-1)+\mu_k\beta-(\rho+\nu\mathbb{1}_{k=1})=0$, $j=1,2$ and $k=1,2,3$.

Proof: The differential equation governing the value function $\Phi_1^{(k)}(\cdot)$ is indicated in (A1). The first term on the left-hand side is the utility of the immediate cash flow and the second term is the expected utility in the continuation region

$$\begin{cases} U\left(\Theta\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)dt + e^{-\rho dt} \\ \left\{\nu dt\mathbb{E}_\Theta\left[\Phi_1^{(k+1)}\left(\Theta+d\Theta\right)\right]\right. \\ \left. +\left(1-\nu dt\right)\mathbb{E}_\Theta\left[\Phi_1^{(k)}\left(\Theta+d\Theta\right)\right]\right\} = 0, \quad k=1 \\ U\left(\Theta\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)dt + e^{-\rho dt}\mathbb{E}_\Theta \\ \left[\Phi_1^{(k)}\left(\Theta+d\Theta\right)\right]=0, \qquad k=2,3 \end{cases} . \quad \text{(A1)}$$

In order to assess the value of a profit stream in the current regime, we let $\Phi_1^{(k+1)}(\Theta)=0$, and using Itô's lemma, we can expand the expressions in (A1) to obtain (A2), and expressing the first term on the right-hand side of (A1) as $U(\Theta(1-\eta Q^{(k)})Q^{(k)})\Theta^\gamma$:

$$\frac{\sigma_k^2}{2}\Theta^{(k)2}\frac{\partial^2}{\partial\Theta^2}\Phi_1^{(k)}\left(\Theta\right)+\mu_k\Theta^{(k)}\frac{\partial}{\partial\Theta}\Phi_1^{(k)}\left(\Theta\right) - \left(\rho+\nu\mathbb{1}_{k=1}\right)\Phi_1^{(k)}\left(\Theta\right) + U\left(\Theta\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)\Theta^{(k)\gamma}=0. \quad \text{(A2)}$$

We conjecture that $\Phi_1^{(k)}(\Theta)=\mathcal{A}^{(k)}\Theta^\gamma$, where $\mathcal{A}^{(k)}$ is a constant to be determined. Substituting this expression into (A2) yields

$$\left[\frac{1}{2}\sigma_k^2\left(\gamma-1\right)\gamma+\mu_k\gamma-\left(\rho+\nu\mathbb{1}_{k=1}\right)\right]\mathcal{A}^{(k)}\Theta^\gamma = -U\left(\Theta\left(1-\eta Q^{(k)}\right)Q^{(k)}\right)\Theta^\gamma. \quad \text{(A3)}$$

Thus, we find that $\mathcal{A}^{(k)} = \frac{-1}{\frac{1}{2}\sigma_k^2(\gamma-1)\gamma+\mu_k\gamma-(\rho+\nu\mathbb{1}_{k=1})} = \frac{\beta_{1\,k}\beta_{2\,k}}{(\rho+\nu\mathbb{1}_{k=1})(\gamma-\beta_{1\,k})(\gamma-\beta_{2\,k})}$. □

Proposition 2: Under a HARA utility function, the optimal investment threshold and optimal capacity in Regime 3 are

$$\Theta_{\tau_1}^{(3)} = \left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}\frac{rb}{1-\eta Q^{(3)}} \quad (13)$$

$$Q^{(3)} = \frac{1}{\eta}\frac{\gamma}{\gamma+\beta_{13}}. \quad (14)$$

Proof: By applying the FONC to the unconstrained optimization problem (12), we obtain

$$\gamma\left(\frac{\Theta}{\Theta_{\tau_1}^{(3)}}\right)^{\beta_{13}}\left[\mathcal{A}^{(3)}U\left(\Theta_{\tau_1}^{(3)}\left(1-\eta Q^{(3)}\right)Q^{(3)}\right)\right] - \beta_{13}\left(\frac{\Theta}{\Theta_{\tau_1}^{(3)}}\right)^{\beta_{13}}\left[\mathcal{A}^{(3)}U\left(\Theta_{\tau_1}^{(3)}\left(1-\eta Q^{(3)}\right)Q^{(3)}\right) - \frac{1}{\rho}U\left(rI^{(3)}\right)\right]=0. \quad \text{(A4)}$$

By solving for $\Theta_{\tau_1}^{(3)}$, we obtain (13). Next, we insert (13) for Θ in the expression for optimal capacity indicated in (11), which yields (14). □

Proposition 3: The objective function $F_1^{(3)}(\cdot)$ is strictly concave at $\Theta_{\tau_1}^{(3)}$ iff $\gamma<\beta_{13}$.

Proof: The SOSC requires that the objective function is concave at the critical threshold $\Theta_{\tau_1}^{(3)}$. Hence, we first need to calculate the second derivative of $F_{\tau_1}^{(3)}(\cdot)$ and evaluate it at $\Theta_{\tau_1}^{(3)}$. We have:

$$\frac{\partial F_1^{(3)}(\Theta)}{\partial\Theta_{\tau_1}^{(3)}} = \beta_{13}\left(\frac{\Theta}{\Theta_{\tau_1}^{(3)}}\right)^{\beta_{13}}\left(-\frac{1}{\Theta_{\tau_1}^{(3)}}\right) \times\left[\mathcal{A}^{(3)}U\left(\Theta_{\tau_1}^{(3)}\left(1-\eta Q^{(3)}\right)Q^{(3)}\right)-\frac{1}{\rho}U\left(rI^{(3)}\right)\right] + \left(\frac{\Theta}{\Theta_{\tau_1}^{(3)}}\right)^{\beta_{13}}\mathcal{A}^{(3)}\Theta_{\tau_1}^{(3)\gamma-1}\left[\left(1-\eta Q^{(3)}\right)Q^{(3)}\right]^\gamma. \quad \text{(A5)}$$

Next, the second derivative is

$$\frac{\partial^2 F_1^{(3)}(\Theta)}{\partial \Theta_{\tau_1}^{(3)^2}} = \left(\frac{\Theta}{\Theta_{\tau_1}^{(3)}}\right)^{\beta_{13}} \Theta_{\tau_1}^{(3)^{-2}} \Bigg(\beta_{13}(\beta_{13}+1) \times \left[\mathcal{A}\frac{\left[\Theta_{\tau_1}^{(3)}(1-\eta Q^{(3)})Q^{(3)}\right]^\gamma}{\gamma} - \frac{1}{\rho}\frac{\left[rbQ^{(3)}\right]^\gamma}{\gamma} \right] - 2\beta_{13}\mathcal{A}\left[\Theta_{\tau_1}^{(3)}(1-\eta Q^{(3)})Q^{(3)}\right]^\gamma + \mathcal{A}(\gamma-1)\left[\Theta_{\tau_1}^{(3)}(1-\eta Q^{(3)})Q^{(3)}\right]^\gamma \Bigg). \tag{A6}$$

The SOSC requires that $\frac{\partial^2 F_1^{(3)}(\Theta)}{\partial \Theta_{\tau_1}^{(3)^2}} < 0$. Substituting for $\Theta_{\tau_1}^{(3)}$, the required condition becomes

$$\mathcal{A}\left[\left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}} \frac{rbQ^{(3)}}{\left(1-\eta Q^{(3)}\right)Q^{(3)}}(1-\eta Q^{(3)})Q^{(3)}\right]^\gamma \times \left(\beta_{13}(\beta_{13}+1) - 2\beta_{13}\gamma + \gamma(\gamma-1)\right) - \frac{\beta_{13}(\beta_{13}+1)}{\rho}\left(rbQ^{(3)}\right)^\gamma < 0. \tag{A7}$$

After simplifying the above expression, we have

$$\frac{\partial^2 F_1^{(3)}(\Theta)}{\partial \Theta_{\tau_1}^{(3)^2}} < 0 \Leftrightarrow \qquad \gamma(\gamma-\beta_{13}) < 0 \tag{A8}$$

which holds for $\gamma < \beta_{13}$. Note that $\beta_{13} > 1$ and, therefore, the objective function is strictly concave for values of γ that imply not only risk-averse by also risk-seeking behavior. ■

Proposition 4: Greater risk aversion lowers the optimal capacity and decreases the required investment threshold.

Proof: Note that all the terms are positive in (A9); thus, the derivative is positive

$$Q^{(3)} = \frac{1}{\eta}\frac{\gamma}{\gamma+\beta_{13}} \Rightarrow \quad \frac{\partial}{\partial\gamma}Q^{^{(3)}} = \frac{1}{\eta}\frac{\beta_{13}}{\left(\gamma+\beta_{13}\right)^2} > 0. \tag{A9}$$

Next, note that

$$\frac{\partial \Theta_1^{(3)*}}{\partial\gamma} = \left(-\frac{1}{\gamma(\beta_{23}-\gamma)} - \frac{\log\left(1-\frac{\gamma}{\beta_{23}}\right)}{\gamma^2}\right)\frac{br\left(\beta_{13}+\gamma\right)}{\beta_{13}} \times \left(1-\frac{\gamma}{\beta_{23}}\right)^{1/\gamma} + \frac{br}{\beta_{13}}\left(1-\frac{\gamma}{\beta_{23}}\right)^{(1/\gamma)} \tag{A10}$$

which can be simplified to obtain

$$\frac{\partial}{\partial\gamma}\Theta_1^{(3)^*} \geq 0 \Leftrightarrow \left(-\frac{1}{(\beta_{23}-\gamma)} - \frac{\log\left(1-\frac{\gamma}{\beta_{23}}\right)}{\gamma}\right) + \frac{\gamma}{\beta_{13}+\gamma} \geq 0. \tag{A11}$$

Hence, we consider the expression $(-\frac{1}{(\beta_{23}-\gamma)} - \frac{\log(1-\frac{\gamma}{\beta_{23}})}{\gamma})$. Note that as $\gamma \to \infty$, the expression tends toward 0. Next, we investigate $\gamma \to 0$ by using L'Hôspital's rule on the second term inside the bracket, which yields $\lim_{\gamma\to 0^+} -\frac{\log(1-\frac{\gamma}{\beta_{23}})}{\gamma} = \frac{1}{\beta_{23}}$, which is exactly offset by the limit of the first term. Furthermore, we have verified that for the considered parameter ranges that the inequality holds.

Proposition 5: Greater demand uncertainty raises the optimal capacity and increases the required investment threshold.

Proof: The objective is to show that $\frac{\partial Q^{(3)}}{\partial\sigma_3} > 0$. Therefore, we have

$$\frac{\partial Q^{(3)}}{\partial\sigma_3} = \frac{\partial}{\partial\sigma_3}\left[\frac{1}{\eta}\frac{\gamma}{\gamma+\beta_{13}}\right] = \frac{1}{\eta}\frac{-\gamma\frac{\partial\beta_{13}}{\partial\sigma_3}}{(\gamma+\beta_{13})^2}. \tag{A12}$$

Consequently, the result follows since $\frac{\partial\beta_{13}}{\partial\sigma_3} < 0$. Next, we consider the optimal investment threshold

$$\Theta_{\tau_1}^{(3)} = \left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}\frac{rb}{1-\eta Q^{(3)}} = rb\left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}\frac{\gamma+\beta_{13}}{\beta_{13}}. \tag{A13}$$

Taking the partial derivative of $\Theta_{\tau_1}^{(3)}$ with respect to σ_3 and noting that $\beta_{13} > 1$ and $\frac{\partial\beta_{23}}{\partial\sigma_3} > 0$, we have

$$\frac{\partial\Theta_{\tau_1}^{(3)}}{\partial\sigma_3} = \frac{rb}{\gamma}\left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}\frac{\beta_{23}}{\beta_{23}-\gamma} \times \frac{\beta_{23}\frac{\partial\beta_{23}}{\partial\sigma_3} - \frac{\partial\beta_{23}}{\partial\sigma_3}\beta_{23} + \frac{\partial\beta_{23}}{\partial\sigma_3}\gamma}{\beta_{23}^2}\frac{\gamma+\beta_{13}}{\beta_{13}} + rb\left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}\frac{\frac{\partial\beta_{13}}{\partial\sigma_3}\beta_{13} - \frac{\partial\beta_{13}}{\partial\sigma_3}\gamma - \frac{\partial\beta_{13}}{\partial\sigma_3}\beta_{13}}{\beta_{13}^2}$$
$$= \underbrace{\frac{rb}{\gamma}\left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}}_{>0}\underbrace{\frac{\beta_{23}}{\beta_{23}-\gamma}}_{>0}\underbrace{\frac{\frac{\partial\beta_{23}}{\partial\sigma_3}\gamma}{\beta_{23}^2}}_{>0}\underbrace{\frac{\gamma+\beta_{13}}{\beta_{13}}}_{>0} \underbrace{- rb\left(\frac{\beta_{23}-\gamma}{\beta_{23}}\right)^{\frac{1}{\gamma}}\frac{\frac{\partial\beta_{13}}{\partial\sigma_3}\gamma}{\beta_{13}^2}}_{<0} > 0. \tag{A14}$$

■

Acknowledgment

The authors would like to express their gratitude for helpful suggestions from Petter Bjerksund and for comments from Afzal Siddiqui during the 41st IAEE International Conference 2018.

References

[1] L. H. R. Alvarez and R. Stenbacka, "Adoption of uncertain multi-stage technology projects: A real options approach," *J. Math. Econ.*, vol. 35, no. 1 pp. 71–79, 2001.

[2] L. H. R. Alvarez and R. Stenbacka, "Optimal risk adoption: A real options approach," *Econ. Theory*, vol. 23, pp. 123–147, 2004.

[3] T. K. Boomsma, N. Meade, and S. E. Fleten, "Renewable energy investments under different support schemes: A real options approach," *Eur. J. Oper. Res.*, vol. 220, no. 1, pp. 225–237, 2012.

[4] M. J. Brennan and E. S. Schwartz, "Evaluating natural resource investments," *J. Bus.*, vol. 58, no. 2, pp. 135–156, 1985.

[5] T. Bøckman, S. E. Fleten, E. Juliussen, H. J. Langhammer, and I. Revdal, "Investment timing and optimal capacity choice for small hydropower projects," *Eur. J. Oper. Res.*, vol. 190, no. 1, pp. 255–267, 2008.

[6] M. Chronopoulos, B. De Reyck, and A. S. Siddiqui, "Optimal investment under operational flexibility, risk aversion, and uncertainty," *Eur. J. Oper. Res.*, vol. 213, no. 1, pp. 221–237, 2011.
[7] M. Chronopoulos, B. De Reyck, and A. Siddiqui, "The value of capacity sizing under risk aversion and operational flexibility," *IEEE Tran. Eng. Manage.*, vol. 60, no. 2, pp. 272–288, May 2013.
[8] M. Chronopoulos and S. Lumbreras, "Optimal regime switching under risk aversion and uncertainty," *Eur. J. Oper. Res.*, vol. 256, no. 2, pp. 543–555, 2017.
[9] M. Chronopoulos and A. S. Siddiqui, "When is it better to wait for a new version? Optimal replacement of an emerging technology under uncertainty," *Ann. Oper. Res.*, vol. 235, no. 1, pp. 177–201, 2015.
[10] A. J. Conejo, L. B. Morales, S. J. Kazempour, and A. S. Siddiqui, *Investment in Electricity Generation and Transmission: Decision Making under Uncertainty*. Cham, Switzerland: Springer, 2016, pp. 308–314.
[11] T. Dangl, "Investment and capacity choice under uncertain demand," *Eur. J. Oper. Res.*, vol. 117, pp. 415–428, 1999.
[12] J. P. Décamps, T. Mariotti, and S. Villeneuve, "Irreversible investment in alternative projects," *Econ. Theory*, vol. 28, pp. 425–448, 2006.
[13] A. K. Dixit, "Choosing among alternative discrete investment projects under uncertainty," *Econ. Lett.*, vol. 41, pp. 265–268, 1993.
[14] A. K. Dixit and R. S. Pindyck, *Investment Under Uncertainty*. Princeton, NJ, USA: Princeton Univ. Press, 1994.
[15] T. P. Filomena, E. Campos-Náñez, and M. R. Duffey, "Technology selection and capacity investment under uncertainty," *Eur. J. Oper. Res.*, vol. 232, no. 1, pp. 125–136, 2014.
[16] S. E. Fleten, K. M. Maribu, and I. Wangensteen, "Optimal investment strategies in decentralised renewable power generation under uncertainty," *Energy*, vol. 32, no. 5, pp. 803–815, 2007.
[17] M. Goto, K. Nishide, and R. Takashima, "Leaders, followers, and equity risk premiums in booms and busts," *J. Bank. Finance*, vol. 81, pp. 207–220, 2017.
[18] S. R. Grenadier and A. M. Weiss, "Investment in technological innovations: An option pricing approach," *J. Financial Econ.*, vol. 44, pp. 397–416, 1997.
[19] V. Hagspiel, P. Jesus, P. M. Kort, and C. Nunes, "How to escape a declining market: Capacity investment or exit?," *Eur. J. Oper. Res.*, vol. 254, pp. 40–50, 2016.
[20] V. Henderson, "Valuing the option to invest in an incomplete market," *Math. Financial Econ.*, vol. 1, pp. 103–128, 2007.
[21] V. Henderson and D. Hobson, "Real options with constant relative risk aversion," *J. Econ. Dyn. Control*, vol. 27, pp. 239–355, 2002.
[22] J. Hugonnier and E. Morellec, "Real options and risk aversion," *Real Options, Ambiguity, Risk Insurance*, vol. 5, pp. 52–65, 2013.
[23] K. Huisman and P. M. Kort, "Strategic capacity investment under uncertainty," *RAND J. Econ.*, vol. 46, no. 2, pp. 376–408, 2015.
[24] International Energy Agency, "World Energy Outlook 2019," Nov. 13, 2019. Accessed: Sep. 16, 2020. [Online]. Available: https://doi.org/10.1787/caf32f3b-en
[25] Independent, "Scottish Power becomes first major UK energy company to generate all electricity from wind," Oct. 16, 2018. Accessed: Sep. 16, 2020. [Online]. Available: https://www.independent.co.uk/climate-change/news/scottish-power-wind-energy-renewable-drax-gas-station-climate-change-a8585961.html
[26] L. Kauppinen, A. S. Siddiqui, and A. Salo, "Investing in time-to-build projects with uncertain revenues and costs: A real options approach," *IEEE Trans. Eng. Manage.*, vol. 65, no. 3, pp. 448–459, Aug. 2018.
[27] E. Lukas, S. Spengler, S. Kupfer, and K. Kieckhäfer, "When and how much to invest? Investment and capacity choice under product life cycle uncertainty," *Eur. J. Oper. Res.*, vol. 260, no. 3, 1105–1114, 2017.
[28] P. Matomäki, *On Two-Sided Controls of a Linear Diffusion*. Turku, Finland: Turku School of Economics, 2013.
[29] L. Maurovich-Horvat, B. De Reyck, P. Rocha, and A. S. Siddiqui, "Optimal selection of distributed energy resources under uncertainty and risk aversion," *IEEE Trans. Eng. Manage.*, vol. 63, no. 4, pp. 462–474, Nov. 2016.
[30] R. L. McDonald and D. S. Siegel, "The value of waiting to invest," *Quart. J. Econ.*, vol. 101, no. 4, pp. 707–728, 1986.
[31] R. L. McDonald and D. S. Siegel, "Investment and valuation of firms when there is an option to shut down," *Int. Econ. Rev.*, vol. 26, no. 2, pp. 331–349, 1985.
[32] R. C. Merton, "Lifetime portfolio selection under uncertainty: The continuous time case," *Rev. Econ. Statist.*, vol. 51, pp. 247–257, 1969.
[33] R. S. Pindyck, "Irreversible investment, capacity choice, and the value of the firm," *Amer. Econ. Rev.*, vol. 78, no. 5, pp. 969–985, 1988.
[34] L. H. Sendstad and M. Chronopoulos, "Sequential investment in renewable energy technologies under policy uncertainty," *Energy Policy*, vol. 137, 2020, Art. no. 111152.
[35] A. S. Siddiqui and S. E. Fleten, "How to proceed with competing alternative energy technologies: A real options analysis," *Energy Econ.*, vol. 23, pp. 817–830, 2010.
[36] A. S. Siddiqui and R. Takashima, "Capacity switching options under rivalry and uncertainty," *Eur. J. Oper. Res.*, vol. 222, pp. 583–595, 2012.
[37] The Economist, "The last Kodak moment?," Jan. 14, 2012. Accessed: Jan. 29, 2015. [Online]. Available: http://www.economist.com/node/21542796
[38] The Economist, "Ericsson and Nokia are now direct rivals. How do they compare?," Mar. 2018. Accessed: Feb. 15, 2021. [Online]. Available: https://www.economist.com/business/2018/03/10/ericsson-and-nokia-are-now-direct-rivals-how-do-they-compare
[39] The Economist, "Ørsted has helped boost the prospects of offshore windpower," Aug. 31, 2019. Accessed: Feb. 15, 2021. [Online]. Available: https://www.economist.com/business/2019/08/31/orsted-has-helped-boost-the-prospects-of-offshore-windpower
[40] The Financial Times, "The disruptive power of renewables," Oct. 16, 2017. Accessed: Feb. 15, 2021. [Online]. Available: https://www.ft.com/content/2490e522-ccc3-3ddf-966a-e12a4865ada8
[41] J. J. Thijssen and D. Bregantini, "Costly sequential experimentation and project valuation with an application to health technology assessment," *J. Econ. Dyn. Control*, vol. 77, 202–229, 2017.